ORIGINAL ARTICLE

Acute effects of force and vibration on finger blood flow

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Objectives: To investigate the effects of contact force at the finger on acute changes in finger circulation during exposure to vibration.

Methods: Each of 10 subjects attended 11 sessions in which they experienced five successive experimental 5-minute periods: (i) no force and no vibration; (ii) force and no vibration; (iii) force and vibration; (iv) force and no vibration; (v) no force and no vibration. During periods (ii) to (iv), the intermediate phalanx of the right middle finger applied one of two forces (2 N or 5 N) on a platform that vibrated during period (iii) at one of two frequencies: 31.5 Hz (at 4 or 16 ms^{-2} r.m.s.) or 125 Hz (at 16 or 64 ms^{-2} r.m.s.). Finger blood flow was measured in the exposed right middle finger, the unexposed right little finger, and the unexposed left middle fingers throughout the 25 minutes of each session.

Results: The application of force alone caused a reduction in finger blood flow in the exposed finger, but not other fingers. There were additional reductions in finger blood flow caused by vibration, with greater reductions at the higher vibration magnitudes at both frequencies but no difference between the two frequencies when using unweighted acceleration. The vibration caused a similar vasoconstriction in vibrated and non-vibrated fingers.

Conclusions: Modest levels of force applied by a finger can have a large effect on the finger blood flow, possibly due to the constriction of local blood vessels. The acute vascular effects of vibration cause additional reductions in finger blood flow that are not limited to the finger experiencing force and vibration. In all fingers (exposed and not exposed to vibration), the greater the magnitude of vibration, the greater the reduction in finger blood flow. In all fingers (exposed and not exposed to vibration), when the vibration was frequency weighted according to current standards, 125 Hz vibration caused greater reductions in finger blood flow than 31.5 Hz vibration.

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Many millions of workers are exposed to hand-transmitted vibration from powered tools and are at risk of developing disorders in the fingers, hands, or arms.[1–4]

One consequence of prolonged regular exposure to hand-transmitted vibration is impaired circulation in the fingers, often evident during or following exposure to cold. The symptoms may be first noticed as abnormally cold fingers, but disorder is often diagnosed from reports of attacks of blanching on the distal, middle, or proximal phalanges. The condition is named "vibration-induced white finger" from the characteristic attacks of blanching that are assumed to be caused by vibration damage, although the attacks are most often provoked by cold.[4] The mechanisms involved in this heightened sensitivity to cold are not known, and so there is uncertainty as to the range of symptoms and signs that characterise the disorder.

Although it is clear that hand-transmitted vibration causes vibration-induced white finger, there is limited evidence as to the characteristics of vibration that are responsible for the injury. To obtain a number indicating the severity of an exposure to vibration (that is, evaluate the vibration), it is necessary to make assumptions as to the importance of the vibration magnitude, the vibration frequency, the vibration direction, the daily exposure duration, and life-time exposure duration. Various standards have made such assumptions so as to define uniform methods for evaluating the vibration on powered tools. Having defined a measure of vibration severity, it is possible to assess the acceptability of the vibration, in terms of the probability or severity of disorder. In International Standard 5349-1 (2001), the evaluation is performed using the root-mean-square value of the vibration acceleration after it has been frequency-weighted (using a weighting called W_h), assuming all directions of vibration to be equally important and all locations of contact with the hand to be equally likely to lead to problems.[5] The assessment of vibration severity uses the 8-hour energy equivalent daily exposure (called $A(8)$) to predict the years of exposure before 10% of persons are likely to develop the first signs of finger blanching.

The frequency weighting inherent in current standards and directives did not evolve from epidemiological studies of the conditions causing vibration-induced white finger, or from experimental studies of the effects of different frequencies of vibration on relevant physiological responses.[6 7] The frequency weighting was largely based on a study of how the discomfort produced by hand-transmitted vibration depends on the frequency of vibration.[8] Some recent epidemiological studies suggest that the frequency weighting may not be optimum and that, at least for the vibration on some groups of common tools, the onset of finger blanching may be predicted with greater accuracy without using frequency weighting W_h.[9] The frequency weighting has a large effect on the relative importance of vibration on different tools and, consequently, on the risks of injury and the responsibilities of employers. Improved understanding of the importance of vibration frequency therefore has considerable importance.

Contact with the vibration on a tool involves the application of force to the fingers. There are tasks that involve the application of a force without exposure to vibration which do not result in the characteristic symptoms of vibration-induced white finger, so force alone cannot explain the disorder. However, force may be expected to have some direct mechanical effect on circulation within the fingers. Furthermore, force may alter the transmission of vibration into the fingers and hand: increased force will tend to stiffen the tissues, which will change resonance frequencies and tend to increase the transmission of vibration from the area of contact with vibration.

Occupational exposures to hand-transmitted vibration result in symptoms of vibration-induced white finger after many months, usually years, of regular exposure to vibration. Laboratory studies have found reductions in blood flow during and following exposure of a finger to vibration. The effects are not restricted to the vibrated finger but are also observed in other fingers, including those on a hand not exposed to vibration. Previous experimental studies by the current authors have explored the effects of the magnitude, frequency, and duration of vibration on finger blood flow using controlled contact areas and controlled contact force.[10–12] The effects of variations in contact force on finger blood flow have not previously been investigated.

This study was designed to investigate whether the force applied by a finger affected finger blood flow and whether the effects of force interacted with the acute effects of vibration. Specifically, it was hypothesised that finger blood flow would be affected by the application of force and that the effects of vibration frequency would be dependent on the force applied to the finger.

SUBJECTS AND METHODS

Subjects

Ten healthy male volunteers, all Caucasian, gave written informed consent to participate in the investigation. All subjects were students or office workers with no history of regular use of hand-held vibrating tools in occupational or leisure activities. Nine subjects were non-smokers. None reported cardiovascular or neurological disorders, connective tissue diseases, injuries to the upper extremities, a history of cold hands, or were on medication. The mean age of the subjects was 27 (SD 2.7; range 22–32) years, their mean stature was 181 (SD 6.3; range 167–186) cm, and their mean weight was 83 (SD 12.8; range 65–100) kg.

The length, breadth, and depth of each phalanx was measured using vernier callipers and the finger volume was calculated. The mean (SD) volume of the middle right finger was 16.3 (3.0) cm^3, the little right finger was 8.1 (1.5) cm^3, and the middle left finger was 14.9 (2.2) cm^3.

Measures of finger circulation

Finger blood flow (FBF) was measured in the middle fingers of both hands and in the little right finger. Mercury-in-silastic strain gauges were placed around the distal phalanx at the base of the nails, and plastic pressure cuffs for air inflation (9.5×2.5 cm) were fixed around the proximal phalanges and secured with a Velcro strip. Three pressure cuffs and strain gauges were connected to a multi-channel plethysmograph (HV*Lab*, ISVR, University of Southampton, UK).

FBF was measured using a venous occlusion technique: the pressure cuffs were inflated to a pressure of 60 mm Hg, and the increases in finger volumes were detected by means of strain gauges according to the criteria given by Greenfield *et al*.[13] FBF measurements were expressed in ml/100 ml/s.

Brachial systolic and diastolic blood pressures were measured in the upper right arm by an ausculatatory technique.

Room temperatures were measured using a thermocouple located adjacent to the subjects' heads.

Experimental procedure

The experiment was performed in a laboratory room with a mean (SD) temperature of 25.6 (0.4)℃. Subjects were requested to avoid caffeine consumption for two hours prior to testing and tobacco and alcohol for 12 hours prior to testing.

Each of the 10 subjects attended the laboratory on 11 occasions. In each session, they experienced five successive experimental periods of 5 minutes: (i) no force and no vibration; (ii) force and no vibration; (iii) force and vibration; (iv) force and no vibration; (v) no force and no vibration.

Throughout each session, subjects lay supine with their hands resting on platforms alongside their body at the level of the heart. After a period of acclimatisation of about 10 minutes, FBF was measured in the right and left middle fingers and the right little finger at 1-minute intervals during the 5 minutes of period (i). The right hand was then moved by the experimenter so that the intermediate phalanx of the right middle finger was positioned on a horizontal wooden platform (40 mm by 20 mm) with the intermediate phalanx across the 20 mm dimension. During period (ii) the subjects were asked to apply a downward force of either 2 or 5 N with the intermediate phalanx of their right middle finger on the platform that was mounted on an electrodynamic vibrator (VP4, Derritron). The signal from a force cell (Tedea Huntleigh) mounted between the platform and the vibrator was used to provide visual feedback on a meter for the control of downward force. The thumb, index, ring, and little fingers of the right hand were suspended in air (fig 1). The left hand remained supported to at heart height to the left of the body.

During period (iii), sinusoidal vertical vibration was presented for 5 minutes, followed by a period with force without vibration during period (iv). The right hand was then moved by the experimenter, so that it was again supported on a platform at heart height alongside the subject for period (v).

The vibration during period (iii) was at one of two levels of 31.5 Hz (4 and 16 ms^{-2} r.m.s. unweighted) or one of two levels of 125 Hz (16 and 64 ms^{-2} r.m.s. unweighted). Using the frequency weighting in current standards, the frequency-weighted vibration magnitudes were 2.0 and 8.0 ms^{-2} r.m.s. at both 31.5 and 125 Hz. The four vibration conditions (31.5 and 125 Hz, at 2.0 and 8.0 ms^{-2} r.m.s., frequency-weighted) were combined with the two levels of force (2 N or 5 N) to give eight experimental conditions with vibration. There were, additionally, two conditions with force (2 N or 5 N) but no vibration and one condition with no force and no vibration, giving a total of 11 conditions (table 1).

For the 5-minute duration of vibration exposure, the 8-hour energy-equivalent frequency-weighted acceleration magnitude (that is, $A(8)$) was 0.204 ms^{-2} r.m.s. in conditions 4, 5, 8, and 9, and 0.816 ms^{-2} r.m.s. in conditions 6, 7, 10, and 11 according to International Standard 5349-1.[5]

FBF was measured at 1-minute intervals in the exposed right middle finger, the unexposed right little finger, and the unexposed left middle fingers throughout the 25 minutes of each condition. The FBF measurements, expressed in absolute values (ml/100 ml/s) and as a percentage of the pre-exposure values, were averaged over the 5 minutes of each exposure period.

Brachial blood pressures were measured at the beginning and at the end of each experimental session. Room temperature was measured at 5-minute intervals.

Each of the 10 subjects experienced all 11 experimental conditions on 11 separate days. Across the subject group, the 11 experimental conditions were presented in a random order. The experimental sessions lasted approximately 40 minutes. All sessions were completed within a 3-week period.

The study was approved by the Human Experimental Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (UK).

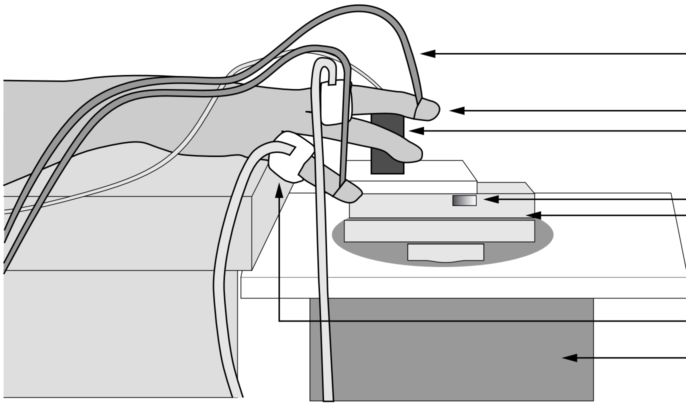

Figure 1 Experimental set up for generating the vibration, controlling the contact force, and measuring finger blood flow.

Statistical methods

Data analysis was performed using the software package Stata (version 8.2 SE). The data were summarised with the mean as a measure of central tendency and the standard deviation (SD) or the standard error of mean as measures of dispersion.

The difference between paired means was tested by Student's *t* test.

Repeated measures analysis of variance (ANOVA) was used to test the hypothesis of no difference in the vascular responses in different exposure conditions. When the compound symmetry assumption (that is, the measures have the same variance and the correlations between each pair of repeated measures are equal) was violated, a conservative test of the repeated measures factor was used by reducing the degrees of freedom of the F ratio (Greenhouse-Geisser method).[14] The 95% Bonferroni confidence intervals for pairwise mean comparisons of the response were used when the probability value for the F test of repeated measures ANOVA was $p < 0.05$ (two sided). The relation between variables with repeated measures was assessed by the generalised estimating equations (GEE) method in order to account for the within-subject correlation.[15]

RESULTS

Figure 2 shows the overall pattern of the mean values of FBF (expressed as ml/100 ml/s and as percentages of the pre-exposure values) in the middle right (exposed, ipsilateral) finger, the little right (unexposed, ipsilateral) finger, and the middle left (unexposed, contralateral) finger across the five exposure periods and the 11 exposure conditions. A repeated measures ANOVA over the whole experiment revealed significant main effects of finger, exposure period, and exposure condition. Two way (e.g. finger × exposure condition) and three-way (finger × condition × period) interaction terms were also found to be significant ($0.05 < p < 0.001$). As a result, data analysis was conducted separately within each finger and across the various exposure periods and exposure conditions.

Finger circulation before exposure

The vascular measurements before exposure to either push force alone or push force and vibration during period (i) (see table 1) showed no significant changes in FBF in either the exposed or the unexposed fingers across the 11 experimental sessions ($p = 0.21$–0.51). During pre-exposure, FBF averaged 1.07–1.34 ml/100 ml/s in the middle right finger, 1.10–1.39 ml/100 ml/s in the little right finger, and 1.16–1.46 ml/100 ml/s in the middle left finger. No differences in the pre-exposure measures of digital circulation were found between the exposed and unexposed fingers within any session.

Brachial systolic and diastolic arterial pressures measured before exposure did not change significantly within subjects across sessions (range of values across subjects and sessions:

Table 1 Experimental design of the study: condition of exposures to push force alone (newtons) and combinations of push force and vibration with two frequencies (Hz) and three acceleration magnitudes (ms^{-2} r.m.s.) having two identical frequency-weighted acceleration magnitudes according to the International Standard 5349-1 (2.0 and 8.0 ms^{-2} r.m.s., see methods)

	Exposure period (time interval)						
	(i) (1–5 min)	(ii) (6–10 min)	(iii) (11–15 min)			(iv) (16–20 min)	(v) (21–25 min)
				Vibration			
Condition	Force (N)	Force (N)	Force (N)	(Hz)	(ms^{-2})	Force (N)	Force (N)
1	0	0	0	0	0	0	0
2	0	2	2	0	0	2	0
3	0	5	5	0	0	5	0
4	0	2	2	31.5	4	2	0
5	0	5	5	31.5	4	5	0
6	0	2	2	31.5	16	2	0
7	0	5	5	31.5	16	5	0
8	0	2	2	125	16	2	0
9	0	5	5	125	16	5	0
10	0	2	2	125	64	2	0
11	0	5	5	125	64	5	0

Condition 1 is a control condition.

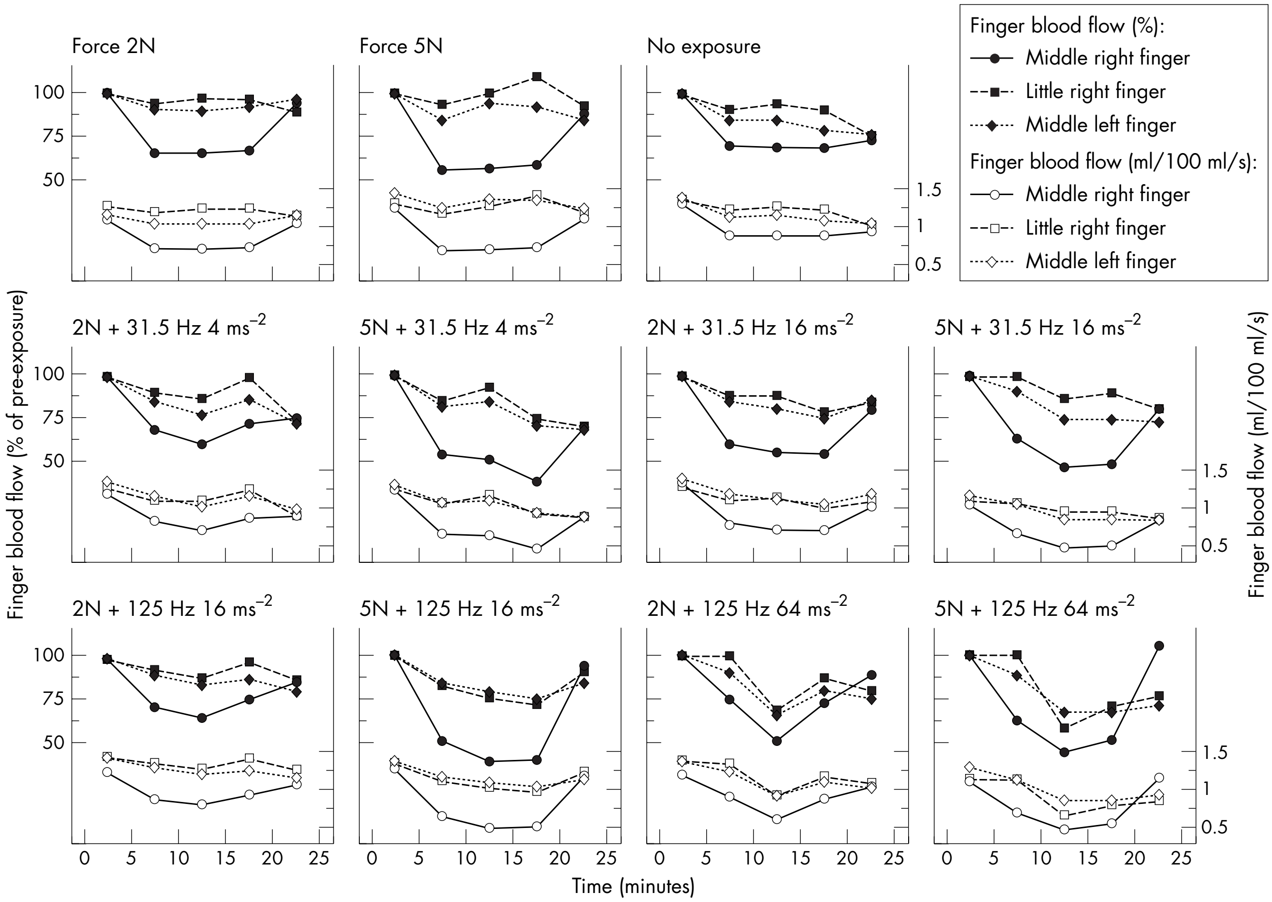

Figure 2 Finger blood flow (ml/100 ml/s) and percentage change of finger blood flow (% of pre-exposure) in the middle right finger (exposed, ipsilateral to push force and vibration), the little right finger (unexposed, ipsilateral), and the middle left finger (unexposed, contralateral) during the various exposure conditions (see table 1). Plotted symbols are mean values. Repeated measures ANOVA: Middle right finger: between exposure conditions, within period (ii), $p=0.025$; between exposure conditions, within period (iii), $p<0.005$; between exposure conditions, within period (iv), $p=0.001$. Little right finger: between exposure conditions, within period (iii), $p<0.001$. Middle left finger: between exposure conditions, within period (iii), $p<0.05$.

115/70–130/80 mm Hg). No difference was observed for the brachial arterial blood pressures measured at the beginning and the end of the 11 sessions.

In the pre-exposure period, period (i), analysis of repeated measures by the GEE method showed no significant relation between FBF and room temperature in either finger.

Neither age nor the volume of the fingers was correlated with the baseline measures of digital circulation.

Repeated measures ANOVA revealed no significant difference in the air temperature of the laboratory across the 11 experimental sessions, ranges of mean (SD) values being 25.3 (0.4) to 25.8 (0.3)℃, ($p = 0.52$–0.90).

Circulatory effects of exposure to push force

Exposure to a push force of 2 N (condition 2) and 5 N (condition 3) alone during periods (ii) to (iv) caused a significant reduction of FBF in the middle right (exposed) finger compared to the pre-exposure period (period (i)) and the recovery period (period (v)) ($p < 0.001$, fig 2). No significant changes in the FBF of the unexposed (ipsilateral and contralateral) fingers were observed during exposure to solely push force of either 2 N or 5 N over the exposure periods from (i) to (v) ($p = 0.39$–0.64).

Relative to blood flow without force during period (ii) in condition 1, exposure of the middle right finger to push force provoked a decrease in the FBF of the exposed finger ($p = 0.025$), whereas there were no significant changes in FBF in the unexposed ipsilateral and contralateral fingers (fig 2 and table 2). When compared with the resting condition (condition 1), a push force of 5 N during period (ii) caused a significant reduction of FBF in the middle right finger ($p < 0.01$). There was no significant difference in the

Table 2 Repeated measures analysis of variance for testing the effects of push force on the percentage change in finger blood flow (% of pre-exposure) at exposure periods (ii) and (iv) (see table 1)

	Middle right finger (exposed, ipsilateral)			Little right finger (unexposed, ipsilateral)			Middle left finger (unexposed, contralateral)		
Exposure period	MS	*F*	p value	MS	*F*	p value	MS	*F*	p value
Period (ii)	1414	3.85	0.025	12	0.02	0.982	79	0.24	0.789
Period (iv)	5002	8.25	0.001	947	1.10	0.337	1062	2.27	0.109

Mean square (MS) values, *F*-statistic, and probability levels for the effect of push force are shown.

Table 3 Repeated measures analysis of variance for testing the effects of push force, vibration frequency, and vibration magnitude on the percentage change in finger blood flow (% of pre-exposure) at exposure period (iii) (see table 1)

	Middle right finger (exposed, ipsilateral)			Little right finger (unexposed, ipsilateral)			Middle left finger (unexposed, contralateral)		
Source of variation	MS	*F*	p value	MS	*F*	p value	MS	*F*	p value
Force	1236	3.34	0.039	44	0.05	0.245	47	0.11	0.899
Vibration frequency	947	2.56	0.083	6556	7.61	0.001	2341	5.34	0.006
Vibration magnitude	533	1.44	0.233	1887	2.19	0.142	1217	2.78	0.099
Force × vibration frequency	268	0.72	0.488	690	0.80	0.452	217	0.50	0.610
Force × vibration magnitude	819	2.22	0.140	17	0.02	0.889	23	0.05	0.819
Vibration frequency × vibration magnitude	17	0.05	0.831	967	1.12	0.292	515	1.18	0.281

Mean square (MS) values, *F*-statistic, and probability levels for the main effects of push force, vibration frequency, and vibration magnitude and for the interaction terms are shown.

change of FBF between the resting condition and a push force of 2 N during period (ii), while 5 N was associated with a greater decrease in FBF than 2 N ($p < 0.05$). However, it should be noted that there was a decrease in the FBF in the middle right finger from period (i) to period (ii) in condition 1 with no force, which was persistent over the remaining exposure periods ($p < 0.05$). A gradual reduction of FBF during condition 1 was also observed in the unexposed fingers from period (ii) to (v), even though repeated measures ANOVA revealed that such a decrease in blood flow was marginally not significant when compared to the pre-exposure (period (i)) ($p > 0.10$).

Circulatory effects of combined exposure to push force and vibration

Repeated measures ANOVA revealed that combined exposure to push force and vibration during period (iii) induced significant changes in the FBF of both the exposed and the unexposed fingers (fig 2). In the middle right (exposed) finger, a multiple comparison test (Bonferroni method) showed that a push force of 5 N combined with 125 Hz vibration at 16 or 64 ms^{-2} r.m.s. (conditions 9 and 11), a push force of 5 N combined with 31.5 Hz vibration at 16 ms^{-2} r.m.s. (condition 7), and a push force of 2 N combined with 125 Hz vibration at 64 ms^{-2} r.m.s. (condition 10) caused a significant decrease of FBF compared to the resting condition with no force and no vibration (condition 1, period (iii)) ($p = 0.01$). Similar results were observed in the little right (unexposed, ipsilateral) finger ($p = 0.03$), and in the middle left (unexposed, contralateral) finger ($p < 0.05$), with the exception of condition 9 (5 N with 125 Hz vibration at 16 ms^{-2} r.m.s.) where the FBF was not significantly different from the resting condition.

In the middle right (exposed) finger, exposure to conditions 9 and 11 (push force of 5 N combined with 125 Hz vibration at 16 or 64 ms^{-2} r.m.s.) during period (iii) caused a more pronounced fall of FBF than condition 2 (push force of 2 N alone), condition 3 (push force of 5 N alone), condition 4 (push force of 2 N combined with 31.5 Hz vibration at 4 ms^{-2} r.m.s.), and condition 8 (push force of 2 N combined with 125 Hz vibration at 16 ms^{-2} r.m.s.) ($p < 0.05$).

In the unexposed ipsilateral and contralateral fingers, exposure of the middle right finger to vibration with force in condition 10 and in conditions 7 and 11 provoked a greater reduction in FBF than exposure to a push force of 2 N and 5 N alone (conditions 2 and 3), respectively.

When the components of the exposure conditions (push force and vibration) were included separately in a repeated measures ANOVA model, some significant main effects of push force and vibration frequency during period (iii) were observed in the exposed (middle right) finger and the unexposed (little right and middle left) fingers, respectively (table 3). Interaction terms between independent variables were not significant in either finger.

To estimate the contribution of vibration to the observed changes in FBF, the difference between the percent change in FBF (% of pre-exposure) at period (iii) and the percent change in FBF (% of pre-exposure) at period (ii) was calculated in order to remove the effect of push force. After subtracting the contribution of force to the change in FBF, the main effects of vibration frequency and vibration magnitude on the reduction of FBF were found to be highly significant in both the exposed and the unexposed fingers (table 4).

Using the same procedure to remove the effect of force, the percentage change in FBF was regressed on the various combinations of vibration frequency and vibration magnitude used in this study (table 5). Assuming condition 1 (no exposure to force and vibration) as the reference category, the GEE method for repeated measures analysis showed that exposure to 125 Hz vibration with an unweighted acceleration magnitude of 64 ms^{-2} r.m.s. caused a significant decrease of FBF in all (exposed and unexposed) fingers. In the little right (unexposed, ipsilateral) finger, the reduction of FBF was significantly greater during exposure to 125 Hz vibration of 64 ms^{-2} r.m.s. than during exposure to any other combination of vibration frequency and magnitude.

A significant main effect of push force on FBF change during period (iv) (exposure to push force alone) was observed only in the middle right (exposed) finger (table 2). Consistent with the findings during period (ii), 5 N during period (iv) induced a greater decrease in the FBF of the exposed finger than either no force or 2 N force ($p < 0.05$). No significant effect of push force was observed in the unexposed ipsilateral and contralateral fingers during exposure period (iv).

Finally, there were no significant changes in FBF in either the exposed or the unexposed fingers during exposure period (v) (that is, recovery) across the 11 experimental sessions ($p = 0.15$–0.48).

DISCUSSION

The decrease in FBF in the middle right finger from period (i) to period (ii) in condition 1 with no force suggests that some factors other than force and vibration had an influence of finger blood flow. In all five periods of each condition, the hand was at the level of the heart, but it was moved laterally by the experimenter at the end of the first five minutes, and before the last five minutes. In conditions 2 to 11 the subject then applied a downward force with the middle phalanx of the middle finger, whereas in condition 1 the hand was in the same posture with the finger resting on the contactor without applying any force. The change in finger blood flow between periods (i) and (ii) in condition 1 may have been associated

Table 4 Repeated measures analysis of variance for testing the effects of push force, vibration frequency, and vibration magnitude on the percentage change in finger blood flow (% of pre-exposure); the change in FBF was calculated as the difference between the percent change in FBF (% of pre-exposure) at exposure period (iii) and the percent change in FBF (% of pre-exposure) at exposure period (ii) (see table 1)

	Middle right finger (exposed, ipsilateral)			Little right finger (unexposed, ipsilateral)			Middle left finger (unexposed, contralateral)		
Source of variation	MS	*F*	p value	MS	*F*	p value	MS	*F*	p value
Force	4	0.01	0.987	3	0.01	0.993	129	0.32	0.724
Vibration frequency	2531	9.03	0.001	8698	19.7	0.001	3494	8.72	0.001
Vibration magnitude	1632	5.82	0.018	6820	15.5	0.001	2310	5.77	0.018
Force × vibration frequency	112	0.40	0.671	392	0.89	0.415	462	1.15	0.320
Force × vibration magnitude	137	0.49	0.486	1109	2.51	0.116	234	0.58	0.447
Vibration frequency × vibration magnitude	74	0.26	0.609	1319	2.99	0.087	67	0.17	0.684

Mean square (MS) values, *F*-statistic, and probability levels for the main effects of push force, vibration frequency, and vibration magnitude and for the interaction terms are shown.

with a change in the height of the finger relative to the heart (by about 10 cm) during the lateral movement needed to place the finger on the wooden platform, or slight compression on the digital arteries when the middle right finger rested on the wooden platform.

In this study, there was a gradual fall in the resting blood flow in the exposed and unexposed fingers over the exposure periods in condition 1. A downward trend in FBF in resting conditions has been observed in other experimental studies and was attributed to both prolonged immobility of the subjects and the prolonged inactivity in their fingers.[16]

Effects of push force

In this study, increasing push forces were associated with increasing reductions of FBF in the exposed finger, while no change in FBF was observed in the unexposed ipsilateral and contralateral fingers. Such a reduction of FBF in the exposed finger is likely due to local mechanical compression of the digital arteries by the applied force. This finding is consistent with those reported in other laboratory investigations which showed a decrease in either finger skin temperature or blood flow when the experimental subjects exerted constant push and/or grip forces on either wooden cylinders or metal handles, suggesting that the forces required to operate vibratory tools can have adverse acute effects on finger circulation.[17–20]

Effects of vibration

After eliminating the effects of force, there was evidence in all fingers (exposed and not exposed to vibration) and at both frequencies (31.5 and 125 Hz) of a greater reduction in FBF with the greater magnitude of vibration. This is consistent with our previous studies.[11 12] That the effect of vibration magnitude is present on unexposed fingers indicates that, unlike the effects of force, the mechanisms responsible for vasoconstriction during exposure to hand-transmitted vibration are not solely local.

After eliminating the effects of force, there was evidence in all fingers (exposed and not exposed to vibration) and at both magnitudes (low and high) of a greater reduction in FBF with the higher frequency of vibration. The low vibration magnitudes (4 ms^{-2} r.m.s. at 31.5 Hz and 16 ms^{-2} r.m.s. at 125 Hz) had the same frequency-weighted acceleration magnitude (2.0 ms^{-2} r.m.s.) according to current standards,

Table 5 Regression of percentage change in finger blood flow (% of pre-exposure) on exposure to push force and vibration; the change in FBF was calculated as the difference between the percent change in FBF (% of pre-exposure) at exposure period (iii) and the percent change in FBF (% of pre-exposure) at exposure period (ii) (see table 1); regression coefficients (robust standard errors) are estimated by the generalised estimating equations method for repeated measures data, assuming no exposure to push force and no exposure to vibration as the reference category; p values are adjusted for multiple comparisons (Bonferroni method)

	Change in finger blood flow (%)		
Predictors	Middle right finger (exposed, ipsilateral)	Little right finger (unexposed, ipsilateral)	Middle left finger (unexposed, contralateral)
Constant (no exposure)	1.7 (6.2)	4.4 (4.5)	4.0 (6.9)
Force 2 N	0.1 (7.9)	0.9 (6.5)	−0.9 (7.5)
Force 5 N	0.0 (8.9)	0.4 (5.2)	0.7 (7.7)
Vibration 31.5 Hz, 4 ms^{-2} r.m.s.	−6.1 (6.2)	−2.3 (7.1)	−6.1 (5.5)
Vibration 31.5 Hz, 16 ms^{-2} r.m.s.	−13.2 (6.1)	−12.6 (6.0)	−15.0 (5.9)
Vibration 125 Hz, 16 ms^{-2} r.m.s.	−11.0 (5.1)	−14.1 (6.3)	−13.0 (6.4)
Vibration 125 Hz, 64 ms^{-2} r.m.s.	−22.0 (5.4)	−40.6 (6.0)	−25.5 (5.3)

Middle right finger
(vibration 125 Hz, 64 ms^{-2}) *v* (no exposure): $p<0.001$.
Little right finger
(vibration 125 Hz, 64 ms^{-2}) *v* (no exposure): $p<0.001$
(vibration 125 Hz, 64 ms^{-2}) *v* (force 2 N): $p<0.001$
(vibration 125 Hz, 64 ms^{-2}) *v* (force 5 N): $p<0.001$
(vibration 125 Hz, 64 ms^{-2}) *v* (vibration 31.5 Hz, 4 ms^{-2}): $p<0.001$
(vibration 125 Hz, 64 ms^{-2}) *v* (vibration 31.5 Hz, 16 ms^{-2}): $p=0.02$
(vibration 125 Hz, 64 ms^{-2}) *v* (vibration 125 Hz, 16 ms^{-2}): $p=0.013$.
Middle left finger
(vibration 125 Hz, 64 ms^{-2}) *v* (no exposure): $p<0.001$.

Main messages

- Increasing contact forces are associated with increasing reductions of finger blood flow in an exposed finger, but not in unexposed fingers.
- There are additional reductions in finger blood flow when contact force is combined with exposure to hand-transmitted vibration.
- The reduction of finger blood flow caused by vibration is not limited to the finger experiencing force and vibration.
- In all fingers (both those exposed and those not exposed to vibration), the higher the frequency of vibration (when using frequency-weighted acceleration) and the greater the magnitude of vibration, the greater the reduction in finger blood flow.

Policy implications

- Minimisation of contact force exerted on tool handle is desirable since the pressure applied to the fingers reduces finger blood flow.
- The frequency weighting for hand-transmitted vibration recommended in ISO 5349-1 (2001) may not predict the vascular responses of fingers to acute vibration.

and the high vibration magnitudes (16 ms^{-2} r.m.s. at 31.5 Hz and 64 ms^{-2} r.m.s. at 125 Hz) also had the same frequency-weighted acceleration magnitude (8.0 ms^{-2} r.m.s.). The high vibration magnitude at 31.5 Hz and the low vibration magnitude at 125 Hz were the same (that is, 16 ms^{-2} r.m.s.), and it may be seen in table 5 that these conditions resulted in similar reductions in FBF relative to the corresponding conditions without vibration. The finding that the same unweighted acceleration gives broadly similar vasoconstriction whereas the same frequency-weighted acceleration does not, is consistent with our previous studies of acute changes in FBF caused by hand-transmitted vibration.[12] It is also consistent with some epidemiological studies of the development of finger blanching in users of vibratory tools.[9]

Influence of push force on the effects of vibration

If the application of force caused a change in the dynamic response of the finger or hand, it would be expected to alter the sensitivity of the finger to changes in FBF at one or both vibration frequencies.

By various means, force applied at the finger could alter the changes in FBF similarly at both frequencies, for example by increasing the transmission of vibration by a similar amount to adjacent tissues. If so, the reductions in FBF with the greater force (5 N) would be expected to differ from those with the lower force (2 N). In the middle right (exposed) finger, exposure to conditions 9 and 11 (push force of 5 N combined with 125 Hz vibration at 16 or 64 ms^{-2} r.m.s.) during period (iii) caused a more pronounced fall of FBF than condition 2 (push force of 2 N alone), condition 3 (push force of 5 N alone), condition 4 (push force of 2 N combined with 31.5 Hz vibration at 4 ms^{-2} r.m.s.), and condition 8 (push force of 2 N combined with 125 Hz vibration at 16 ms^{-2} r.m.s.) ($p < 0.05$), consistent with a force of 5 N with vibration producing a greater decrease in FBF than either 2 N or 5 N alone, and greater than with 2 N combined with vibration.

Comparison of results with our previous studies

In respect of the effects of vibration magnitude and vibration frequency, the results are consistent with our previous findings: greater reduction in FBF with greater magnitudes and greater reductions with higher frequencies when vibrations of equal frequency-weighted vibration are compared.[11 12] However, the effects of force appear somewhat different from our previous research.

In previous studies,[10 12] no difference has found between finger blood flow measured with and without force, but the contact conditions were not identical to those used here. Bovenzi *et al*[10 12] applied a 10 N downward force on a flat wooden plate with the right hand such that the pressure was exerted over the phalanges of several fingers, and found no effect of force on FBF. In this study, lower forces (2 and 5 N) resulted in clear reductions in FBF but the force was exerted solely by the middle phalanx of the middle finger. An obvious possible explanation is that the increased pressure at this location may have compressed the vasculature sufficiently to impair circulation.

Consequences for vibration evaluation and assessment

Since the pressure applied to the finger in this study resulted in reduced finger blood flow without vibration, it is reasonable to wonder to what extent the pressures associated with the grips applied to the handles of tools also reduce finger blood flow. It is often assumed that a minimisation of grip force is desirable because it may reduce the transmission of vibration to the hand. Since grip can reduce finger blood flow, this is an additional reason for recommending the minimisation of grip forces and, further, the investigation of grip designs to minimise the reduction in finger blood flow.

Contact between the hand and vibratory hand tools is not limited to the fingers but extends into the palm of the hand. Further study of the effects of force, pressure, and contract location in the palm of the hand is desirable so as to identify means of holding tools with minimum effects of finger blood flow.

Conclusions

Forces as low as 2 N and 5 N applied to a finger can greatly reduce blood flow in the finger to which force is applied. The acute vascular effects of vibration cause reductions in finger blood flow that are additional to the reductions caused by force and are not limited to the finger experiencing force and vibration. In all fingers (both those exposed and those not exposed to vibration), the greater the magnitude of vibration, the greater the reduction in finger blood flow. In all fingers (exposed and not exposed to vibration), when the vibration was frequency-weighted according to current standards, vibration at 125 Hz caused a greater reduction in finger blood flow than vibration at 31.5 Hz.

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REFERENCES

1 **Griffin MJ**. *Handbook of human vibration*. London: Academic Press, 1990.
2 **Griffin MJ**. Measurement, evaluation, and assessment of occupational exposures to hand-transmitted vibration. *Occup Environ Med* 1997;**54**:73–89.
3 **Comité Européen de Normalisation**. *Mechanical vibration—guide to the health effects of vibration on the human body*, CEN Report 12349. Brussels, 1996.
4 **Griffin MJ**, Bovenzi M. The diagnosis of disorders caused by hand-transmitted vibration: Southampton Workshop 2000. *Int Arch Occup Environ Health* 2002;**75**:1–5.
5 **International Organization for Standardization**. *Mechanical vibration—measurement and evaluation of human exposure to hand-transmitted vibration. Part 1: General requirements.* ISO 2001: 5349-1. Geneva: ISO, 2001.
6 **Bovenzi M**, Lindsell CJ, Griffin MJ. Response of finger circulation to energy equivalent combinations of magnitude and duration of vibration. *Occup Environ Med* 2001;**58**:185–93.
7 **Griffin MJ**. Minimum health and safety requirements for workers exposed to hand-transmitted vibration and whole-body vibration in the European Union; a review. *Occup Environ Med* 2004;**61**:387–97.
8 **Miwa T**. Evaluation methods for vibration effects. Part 4: Measurement of vibration greatness for whole-body and hand in vertical and horizontal vibration. *Ind Health* 1968;**6**:1–10.
9 **Griffin MJ**, Bovenzi M, Nelson CM. Dose-response patterns for vibration-induced white finger. *Occup Environ Med* 2003;**60**:16–26.
10 **Bovenzi M**, Lindsell CJ, Griffin MJ. Duration of acute exposures to vibration and finger circulation. *Scand J Work Environ Health* 1998;**24**:130–7.
11 **Bovenzi M**, Lindsell CJ, Griffin MJ. Magnitude of acute exposures to vibration and finger circulation. *Scand J Work Environ Health* 1999;**25**:278–84.
12 **Bovenzi M**, Lindsell CJ, Griffin MJ. Acute vascular response to the frequency of vibration transmitted to the hand. *Occup Environ Med* 2000;**57**:422–30.
13 **Greenfield ADM**, Whitney RJ, Mowbray JF. Methods for the investigation of peripheral blood flow. *Br Med Bull* 1963;**19**:101–9.
14 **Greenhouse SW**, Geisser S. On methods in the analysis of profile data. *Psychometrika* 1959;**24**:95–111.
15 **Diggle PJ**, Liang KY, Zeger SL. *Analysis of longitudinal data*. Oxford Statistical Science Series No.13. Oxford: Oxford University Press. 1994.
16 **Egan CE**, Espie BH, McGrann S, *et al*. Acute effects of vibration on peripheral blood flow in healthy subjects. *Occup Environ Med* 1996;**53**:663–9.
17 **Sandover J**, Louw J. Acute effects of grip force and vibration on finger temperature. In: Dupuis H, Christ E, Sandover J, Taylor W, Okada A, eds. *Proceedings of the 6th International Conference on Hand-Arm Vibration.* ISBN: 3-88383-331-2. Bonn: HVBG, D-53754 Sankt Augustin, 1992:211–18.
18 **Scheffer M**, Dupuis H. Effects of combined hand-arm vibration and cold on skin temperature. *Int Arch Occup Environ Health* 1989;**61**:375–8.
19 **Hartung E**, Dupuis H, Scheffer M. Effects of grip and push forces on the acute response of the hand-arm system under vibrating conditions. *Int Arch Occup Environ Health* 1993;**64**:463–7.
20 **Miyakita T**, Miura H, Futatsuka M. Hand-arm vibration, noise, temperature and static load—an experimental study of peripheral circulation while operating chain-saws. *Kurume Medical Journal* 1990;**37**(suppl):S73–83.

ECHO

Flexible contracts have psychosocial consequences

Please visit the *Occupational and Environmental Medicine* website [www.occenvmed.com] for a link to the full text of this article.

Unravelling the complexities of flexible contracts on health is just beginning, with a study of Spanish workers showing that the type of contract, health indicator chosen, and interaction between sex and social class affect their impact.

What seems clear so far is that open ended contracts damage mental health in lower social classes and temporary contracts in general delay partnerships and becoming a parent, but mainly in men.

The cross sectional study is the first of its type in Spain. It was based on a subsample aged 16–64 years of the 2002 Catalonian health survey cohort in permanent jobs or temporary jobs with fixed or non-fixed term contracts or no contracts. Jobs with no or non-fixed term contracts were most associated with poor mental health in disadvantaged workers—women and manual worker men—with age adjusted odds of poor mental health over 2–3 times or over 4–6 times that, respectively, for permanent workers. Fixed term contracts were not associated with poor mental health, though disparate situations within these might mask an effect, as other studies have recorded a link. Lastly, any temporary contract or no contract was associated with remaining single and not having children, especially in men.

Temporary contracts are becoming the norm globally and are common in Spain. So far, studies have recorded poorer health with workers' perceived precariousness of their jobs, but results have been inconsistent in the few that have researched a link between health and contract type.

▲ Artazcoz L, *et al. Journal of Epidemiology and Community Health* 2005;**59**:761–767.